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CONTRIBUTIONS FROM THE JEFFERSON PHYSICAL LABORATORY, HARVARD UNIVERSITY.

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By B. Osgood Peirce.

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In 1863, von Waltenhofen, who had been making experiments upon the retentiveness of bars of iron and steel for magnetism, discovered the phenomena which usually bear his name. If an increasing current (I), ending in the maximum value I', be sent through a long solenoid, the final value of the magnetic moment of a solid bar of originally demagnetized soft iron or steel within the solenoid frequently depends, not only upon the final strength of the current, but also upon the manner of growth of the current in attaining this intensity. The moment will be greater if the current be suddenly applied in full strength than if it be made to grow slowly, either continuously or by short steps. If, after the current has remained steady for a short time, at the strength I', it be made to decrease to zero, the residual moment of the bar will usually be less if the current be suddenly opened than if the decrease be made slowly, by gradually introducing more and more resistance, and the demagnetizing factor of a given cylinder is considerably less when computed from observations made by the method of sudden reversals, than if it is determined by slow, step-by-step changes in the exciting current.

Von Waltenhofen also encountered some cases of apparently anomalous magnetization which he describes in the following words taken from his paper in Volume 120 of Poggendorff's Annalen:

"Es ist mir oft aufgefallen, dass die magnetischen Rückstände in weichen Eisenkernen bei wiederholter, ganz gleicher, temporärer Magnetisirung desselben Stabes, sehr ungleich ausfallen. Noch befremdender aber war mir eine Erscheinung, die ich an einem sehr dicken Eisencylinder zuerst wahrgenommen habe, und welche darin bestand, dass der nach Aufhebung des magnetisirenden Stromes zurückgeblie-

bene Magnetismus im Vergleiche mit dem verschwundenen temporären Magnetismus manchmal sogar die entgegengesetzte Polarität hatte. . . . In der Magnetisirungsspirale wurde ein vollkommen unmagnetischer Cylinder von möglichst weichem Eisen, 103 mm. Länge und 28mm. Durchmesser, mit zunehmender Stromintensität soweit magnetisirt, dass sein temporäres Moment nahezu = 60 war. Nach plötzlicher Stromunterbrechung äusserte er das entgegengesetzte remanente Momente —0.20, und zeigte auch nach wiederholten plötzlichen Oeffnungen der wieder geschlossenen Kette entschieden negative (anomale) Rückstände. Dagegen zeigte sich nach allmählich eingeleiteter Aufhebung des magnetisirenden Stromes jedesmal ein bedeutendes, mit dem temporären Momente gleichnamiges Residuum. Wenn der Strom hierauf in derselben Richtung abermals hergestellt, sodann aber plötzlich unterbrochen wurde, zeigte sich das mit der temporären Magnetisirung gleichnamige Residuum, welches nach allmählicher Stromaufhebung immer wenigstens den Betrag 0.30 hatte, nahezu auf 0 reducirt; konnte jedoch durch Wiederholung dieses Verfahrens nicht merklich unter 0 herabgebracht werden. Wenn aber hierauf die magnetisirende Stromrichtung gewechselt wurde, so trat nach plötzlicher Unterbrechung wieder eine ganz entschiedene anomale Magnetisirung auf. So oft der Eisencylinder mehrere Tage in ostwestlicher horizontaler Lage unberührt gelassen war, zeigte er sich wieder vollkommen unmagnetisch, und ergab bei Wiederholung des zuerst beschriebenen Versuches wieder das anomale Residuum —0.20. Wenn dagegen die remanenten Magnetismen nicht durch längeres Liegenlassen, sondern durch entmagnetisirende Ströme verschwinden gemacht worden, gelang es nicht, so auffallende anomale Magnetisirungen hervorzubringen."

Seventeen years after the publication of von Waltenhofen's results,[1] Righi,[2] who was apparently unacquainted with his work, printed in the Comptes Rendus an account of some similar experiments of his own. He says: "On sait que le rapport entre le magnétisme rémanent et le magnétisme temporaire d'une barre d'acier envelopée par une bobine magnétisante devient de plus en plus petit si la barre est de plus en plus courte et grosse." "Si l'on prend des barres d'un même acier et de même diamètre mais de longueurs décroissantes, on doit arriver à une certaine longueur qui ne donne pas de magnétization, pendant qu'avec des longueurs moindres on doit obtenir une polarité rémanente opposée à celle de la bobine." "Si le courant est très fort, le phénomène de la polarité anomale ne se produit qu'après avoir magnétisé la barre quelquefois dans les deux sens."

[1] A. v. Waltenhofen, Pogg. Ann., **120**, 1863.
[2] A. Righi, Comptes Rendus, **90**, 1880.

During the last thirty years, many persons[3] have studied the von Waltenhofen phenomena as they affect the hysteresis cycles of straight rods and of closed cores of iron, and some of these have discussed the bearing of their own measurements upon the theory of anomalous magnetization. G. Wiedemann[4] always maintained that his own researches and those of Righi showed that eddy currents in the iron, accompanying surges in the exciting circuit, accounted best for the observed facts. It seemed to von Waltenhofen, however, that the strange reversals of polarity which he had noticed could not be due to induced currents caused by sudden changes in the exciting circuit, and he explained them as consequences of the inertia of the molecular magnets turning in a viscous medium. Fromme,[5] Auerbach, Ewing, Peuckert, Zielinski, and others who have written upon the subject, seem to agree on the whole with von Waltenhofen's views.

The present paper attempts to throw some light upon the theory of the von Waltenhofen effect by a discussion of a number of experiments made for the purpose of determining the conditions under which anomalous magnetization appears. It leaves to a future article a consideration of some of the theoretical aspects of the subject.

The Demagnetizing of Stout Pieces of Iron or Steel.

It is to be said at the outset that almost every piece of iron to be obtained nowadays in the market is more or less strongly magnetized

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[3] C. Fromme, Wied. Ann., **5**, 1878; **13**, 1881; **18**, 1883; **33**, 1888; **44**, 1891. F. Auerbach, Wied. Ann., **14**, 1881; **16**, 1882; Winkelmann's Handbuch der Physik, Bd. V (214). W. Peuckert, Wied. Ann., **32**, 1887. P. Bachmetjeff, Rep. der Physik, **27**, 1891. Zielinski, Mitt. a. d. Telegraph-Ing.-Bureau d. Reichspostamtes, **2**, 1896. Ruecker, Inaugural Dissertation, Halle-Wittenberg, 1905. Peirce, These Proceedings, **43**, 1907; **46**, 1911. L. A. Babbitt, These Proceedings, **47**, 1911.

[4] "Schon bei Gelegenheit der von Righi wiederholten Versuche von v. Waltenhofen über die anomale Magnetisirung, hatte Ref. [Wiedemann] erwähnt, dass sich dieselben völlig aus dem Auftreten alternirender Inductionsströme in der Masse des Eisens beim schnellen Oeffnen des magnetisirenden Stromes u. s. f. ableiten lassen, von denen ein später auftretender weniger dichter, die Magnetisirung durch einen vorhergehenden dichteren Strom vernichten resp. umkehren kann. Die anomale Magnetisirung ist also *rein secundär*." — Beiblätter der Annalen der Physik, **5**, 1881.

[5] "Gegenüber den Bemerkungen des Herrn Ref. [Wiedemann] halte ich meine Ansicht aufrecht, dass ich durch meine Versuche mit Eisendrahtbündeln, welche ebenfalls den Unterschied der permanenten Momente in der regelmässigsten Weise zeigten, schon nachgewiesen zu haben glaube, dass Inductionsströme keinesfalls zur Erklärung ausreichen können." — Wiedemann's Annalen, **13**, 1881.

when it comes into the hands of the observer, and that it is often very difficult, if not impossible, to demagnetize a massive block thoroughly. If a slender rod be placed inside a long solenoid in circuit with the secondary coil of a suitable open-core transformer, and if this coil be slowly drawn off the core with the help of some mechanical device, it is possible to send through the solenoid a long series of currents, alternating in direction and gradually decreasing in intensity, and thus to demagnetize the rod well enough for most purposes. The Jefferson Laboratory has three large sets of apparatus of this sort.

The process just described, however, does not succeed very well with stouter rods, for several seconds may be required to establish a steady current in the solenoid under a steady electromotive force if the core be large, and the use of alternating currents of commercial frequencies is barred out. The solenoid current may be reversed in such a case, at sufficiently long intervals, by means of a mercury commutator geared to an electric motor. Such a commutator, made several years ago by Mr. George W. Thompson, the mechanician of the Jefferson Laboratory, enabled Mr. L. A. Babbitt [6] to demagnetize very completely the finely divided core of a large toroidal transformer, though a number of hours were spent each time in the process. With irregular masses of metal this process also is often ineffective, and it is not always successful with short cylinders. A piece of soft Bessemer steel 5 centimeters long, recently cut from a long rod 3 centimeters in diameter, in the Jefferson Laboratory, was found to be slightly magnetized, and Mr. Thompson and Mr. John Coulson attempted to demagnetize it in a solenoid about 38 centimeters long, consisting of about 1460 turns of large wire. They began the series of alternately directed and slowly decreasing currents with one of more than 40 amperes, corresponding to a field within the solenoid before the iron was introduced of about 1700 gausses, but the iron was still magnetized in the old direction, with nearly the same intensity, at the end of their work.

In demagnetizing a stout piece of iron by currents alternating in direction, it is well to put the metal slowly through a succession of complete hysteresis cycles with gradually decreasing ranges, but if this be inconvenient, the iron may be surrounded by a thick copper shell,[7] the eddy currents in which will prevent the magnetic changes in the iron caused by a sudden reversal of the main switch from being so violent as they otherwise might be. As will appear more clearly in the sequel, the distribution of the magnetization in a stout iron cylinder

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[6] These Proceedings, **47**, 1911.
[7] Shuddemagen, These Proceedings, **43**, 1907.

in a solenoid which carries a current of given strength is different according as the current attained its final value slowly or suddenly, and it very much facilitates the demagnetization of such a piece, if the currents be applied slowly and decreased gradually.

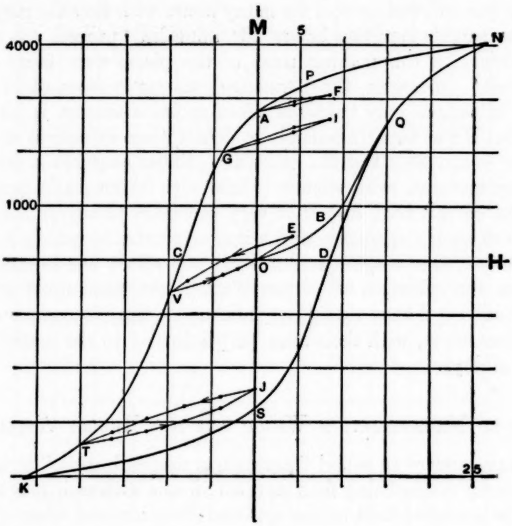

FIGURE 1.

It is often assumed that a piece of iron may always be completely demagnetized by heating it uniformly nearly to a white heat, maintaining it at this high temperature for some time, and then allowing it to cool slowly in a place where it will not be exposed to any magnetic forces; but in practice the procedure often fails, especially with material which has once been irregularly magnetized or which is not quite homogeneous. The spherical shield of a new DuBois-Rubens Panzer Galvanometer in the Jefferson Laboratory proved to be slightly magnetized and consequently useless for the purpose for which it was made. This was heated to nearly a white heat, kept hot for about half an hour, and then very slowly cooled in a protected space, without causing it to lose appreciably its original magnetization; a repetition of the process was also unsuccessful.

Most of the specimens mentioned in the experiments discussed below were packed, one or two at a time, in fine iron filings, enclosed in a piece of large iron pipe provided with screw caps at the ends, and then heated thoroughly for some time, under a power blast, in a gas furnace. The pipe was surrounded by fire bricks and after the fire had been removed it was allowed to cool for many hours with its axis perpendicular to the earth's meridian before the annealing process was regarded as complete. In this manner most of the pieces were fairly well demagnetized. Of course, the permanent magnetic moment of an iron cylinder of length only twice as great as its diameter, is never very strong, but it was usually possible to detect some evidences of magnetization in every piece tested. A stout cylinder acquires a fairly large temporary moment, even when it is held with its long axis perpendicular to the earth's field, and it is very necessary to adjust the relative positions of such a specimen and a magnetometer by which it is to be tried, so that this magnetization shall not affect the measurements. The short iron cylinders which von Waltenhofen used must have been very soft indeed if they really lost their magnetization completely when left to themselves, with their axes perpendicular to the meridian, for a number of days.

Cases of Magnetization Which are not Really Anomalous.

In many cases of so called "anomalous magnetization," it is evident that a strong magnetizing field applied in one direction has been succeeded by a weaker field in the opposite direction, and when this latter has been removed, the magnet has the polarity of the first field. This is of course not wonderful except as we may regard all hysteresis phenomena as mysterious. Figure 1 shows a hysteresis diagram for an iron rod about 80 diameters long, with a number of loops corresponding to "side trips" within the main figure. It is clear that if the rod has been magnetized by a positive current so that the magnetic condition while the current is flowing is represented by the point N, and if the current be then stopped so that the condition of the rod is denoted by A and an oppositely directed current which gives rise to a field not greater than the abscissa of the point V be applied and then removed, the resulting magnetization of the rod will be represented by some point of the line OA. If the negative field is greater than OC, the polarity of the rod while the current is on will be negative, but if it be not too strong the polarity will be positive when the field is off. This phenomenon is relatively pronounced in the case of a short, stout rod where OA is short and the slope of the lower side of an inner loop

is almost parallel to the line KVAN which may be nearly straight. An example will make this statement clearer.

Table I. gives the material for a kind of hysteresis diagram for a certain round rod of hardened tool steel, 2.8 cm. in diameter, and 12 cm.

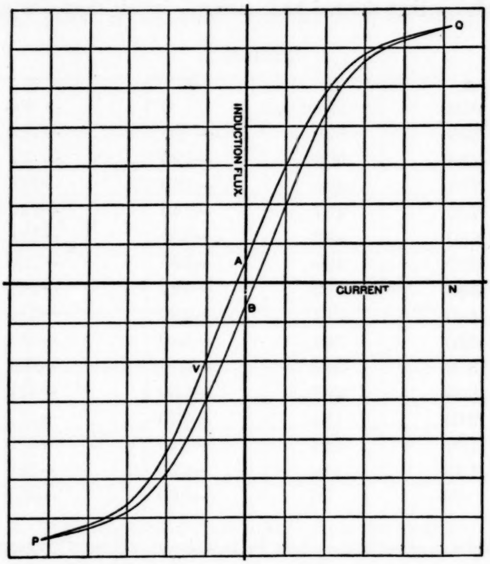

FIGURE 2. Magnetic cycle for a piece of Seebohm and Dickstahl's special magnet steel 12 centimeters long and 3.5 square centimeters in cross section. If the exciting current be dropped from its highest strength to 0, and then reversed and given such a strength as to carry the magnetism to the negative value represented by the point V, the residual magnetism will be slightly positive when the current is taken off.

long, when magnetized in a certain long solenoid. The column headed "H" gives the strengths in gausses which the fields within the solenoid would have if the rod were not there; the strengths of the exciting fields in the rod would be very hard to determine even if they did not vary from point to point in the metal. The numbers under "N" are proportional to the flux strengths through the central cross section of the rod.

If a positive current corresponding to $H = 976$ were sent through the solenoid and were then stopped, a negative current corresponding

to $H = -35$ would make the magnetization of the rod negative while running, but a negative current corresponding to $H = -150$ could be used without making the magnetization negative when the current was taken off. A case like this may puzzle the observer if he does not happen to know that the rod he is using — which does not seem to be

TABLE I.

H.	N.	H.	N.
960	551	0	+ 24
900	530	− 60	− 18
840	509	−120	− 61
780	489	−180	−103
720	467	−240	−137
660	443	−300	−191
600	420	−360	−231
540	392	−420	−272
480	361	−480	−316
420	321	−540	−354
360	279	−600	−391
300	237	−660	−422
240	195	−720	−451
180	144	−840	−504
120	110	−900	−528
60	66	−960	−551

very strongly magnetized — has in fact been exposed to some very intense field in the process of manufacture, but this phenomenon is very different from the one which von Waltenhofen describes.

The Anomalous Magnetization of Short Cylinders.

The most characteristic examples of really reversed magnetization are to be found, perhaps, among short, stout rods of soft iron and steel, as von Waltenhofen and Righi explained many years ago. If such a rod, originally annealed and demagnetized, be placed within a long solenoid and be subjected to a magnetizing field of suitable strength, and if the exciting current be then gradually reduced to zero by the introduction of more and more resistance into the circuit — by very small steps, if not continuously — the remanent magnetism will have the same sign as, but only a small fraction of the strength of, the magnetization induced in the rod when the current was running. If, however, the current be suddenly interrupted by the opening of the circuit,

it frequently happens that the sign of the residual moment is opposite to that while exposed to the field. Figure 3 shows a typical case of a certain kind, that of a solid piece of carefully annealed "Cold Rolled Shafting" 8 centimeters long and 3 centimeters in diameter. The "demagnetizing effect of the ends" in a rod of these dimensions is, of

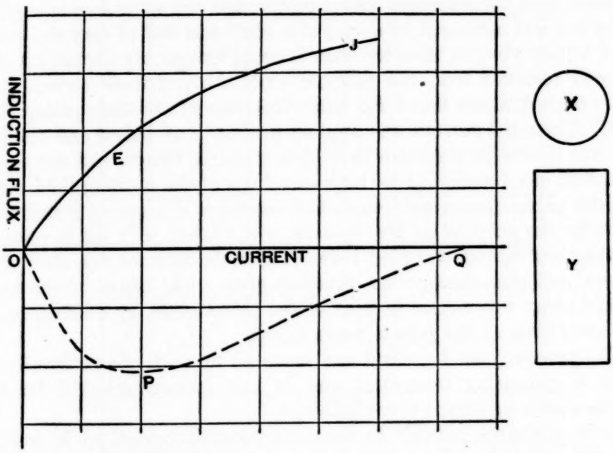

FIGURE 3. The ordinates of these curves show the magnetic condition of a soft cylinder of mild steel 8 centimeters long and 3 centimeters in diameter, when the exciting current had been taken off — gradually, in the case of the full curve — suddenly in the case of the curve OPQ in which the negative ordinates indicate anomalous magnetization.

course, very great, and the residual moment in this instance was for many currents less than one per cent of the moment originally induced in the metal. The long, uniformly-wound solenoid used for this experiment had a number (n) of turns per centimeter of its length such as to make $4\pi n/10$ almost exactly 25. In the figure, which represents a large number of observations, the horizontal unit corresponds to a field of 100 gausses if the iron were taken out of the solenoid. The actual field to which any portion of the rod was exposed for any value of the exciting current was of course difficult to determine. When the exciting current was suddenly broken a small spark appeared, and if the strength of the current was not greater than about 30 amperes, the remanent moment was of reversed sign.

The rod was at the outset in a nearly neutral condition. A small current (i) was at first applied to the solenoid, and then, with the help of a set of high-resistance rheostats made by the Simplex Electric Company, the rod was put many times through a hysteresis cycle with this current, positively or negatively directed, to mark the limits. After this the same current was slowly applied again and gradually removed, and the remanent induction through the central cross section of the rod was measured by means of a small test coil of very fine insulated copper wire, so mounted that it could be quickly slipped off the rod and removed from the solenoid while the rod itself remained in situ. This flux was found for both directions of the magnetizing current. Then the current was applied gradually as before and the circuit was broken by a sudden blow upon a simple switch, and the remanant flux was determined for both directions of the exciting field. The ballistic galvanometer used was a low-resistance d'Arsonval instrument made for the purpose by Mr. Coulson, who worked with me in making all the observations recorded here. The scale distance was about five meters, and the telescope was focussed upon a real image of the scale formed about two meters in front of the object glass, by a lens used as the cover glass of the galvanometer mirror.

The process just described was repeated for each of a series of currents of increasing intensities, and in this manner material for the curves shown in Figure 3 was obtained.

It is, of course, possible to use a magnetometric method in testing the residual magnetism of short rods, but although we have made a large number of determinations in this way, we have found it inconvenient for several reasons. It will appear later that the lines of magnetization in the case of an anomalously magnetized rod are so folded together that the external effect of the remanent magnetism is usually small, and if a conveniently large magnetometer deflection is to be obtained, the rod must be very near to the needle. It is not safe to remove the iron from the solenoid in order to test it outside, for a slight blow might seriously alter the moment, and if the magnetism is to be measured while the specimen is in its place within the solenoid, the magnetometer must be set up near one end of the solenoid, where it will be violently disturbed by the exciting currents and the fields incident to the process of forcing the iron so many times through the hysteresis cycles by which it is prepared for the tests. If a stout specimen of soft iron is placed with its axis horizontal and perpendicular to the meridian, a moment large compared with the residual moment to be measured is induced in it by the earth's field, and it is practically difficult to prevent this transverse magnetization from masking the effect to be measured.

In all the observations mentioned in this paper the solenoid was placed with its axis perpendicular to the meridian, and in all but a very few instances to be mentioned specially, the rod was tested while inside the solenoid.

In almost every instance, also, the exciting current was applied

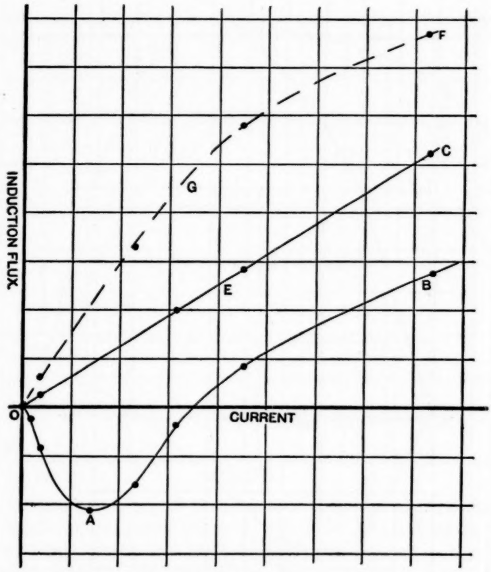

FIGURE 4. OGF and OAB show the flux of magnetic induction through a rod of very soft steel 2.86 cm. in diameter and 12 cm. long, after the magnetizing field had been gradually and quickly removed, respectively. OEC shows on a reduced scale the flux in the rod while it was exposed to the magnetizing field.

slowly to the magnetizing coil. That is, the circuit was closed with a very much greater resistance in it than was finally needed, and this was gradually reduced to the proper amount. If the circuit was suddenly closed with this final resistance in it, the residual moment of the rod was much smaller in absolute value, whether the current had been gradually or suddenly reduced to zero, than if the rise of the current had been slower.

Figure 4 shows the results of tests similar to those described above,

but made upon a phenomenally soft bar of mild steel 12 centimeters long and about 2.86 centimeters in diameter. The line OEC, which is nearly straight, represents the induction flux through the central cross

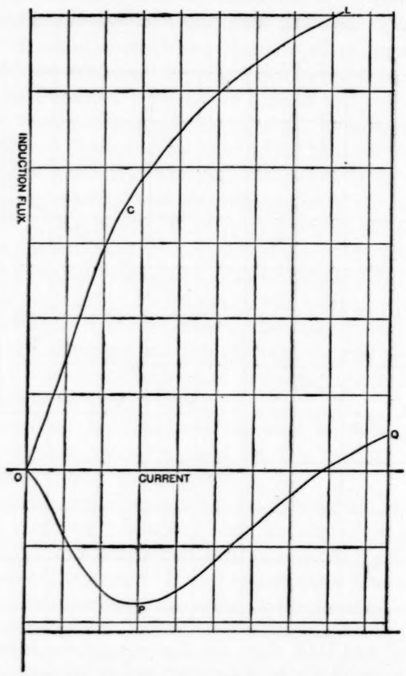

FIGURE 5. A cylindrical shell, about 12 centimeters long and 2.8 centimeters in outside diameter, was exposed in a long solenoid to exciting currents of various intensities. OCL represents the flux through the central cross section of the cylinder when the current was running, and OPQ, drawn on a somewhat exaggerated scale, the remanent flux when the circuit was suddenly broken. The horizontal unit corresponds to a field of 25 gausses in the solenoid when the iron was not there.

section of the bar while the metal was under the action of the magnetizing field. Each ordinate has only one nine-hundredth of the length it would have if the scale of this curve were the same as for the other lines in the figure. The ordinates of OGF give the remanent flux when the slowly applied exciting current was as slowly reduced to

zero. The line OAB shows the residual flux after the current had been suddenly interrupted. The solenoid used in this work has 1460 turns in a length of 47 centimeters. The horizontal unit in the diagrams corresponds to about 80 gausses for the field ($4\pi n\, I/10$) in the solenoid due to the current in its coil. A discharge of 1 microcoulomb

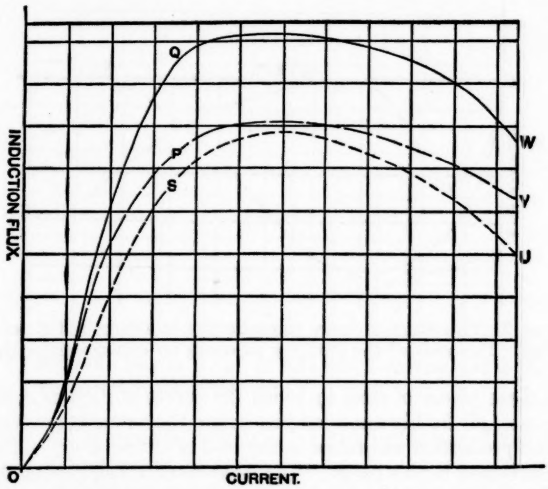

FIGURE 6. The ordinates of these curves represent the residual magnetism in a certain short, stout piece of soft steel magnetized in a solenoid, when the exciting current had been suddenly interrupted. A positive ordinate indicates reversed or anomalous magnetization. The observations recorded in each curve were taken after the specimen had been newly annealed, and the differences between the curves show that it is difficult to demagnetize a cylinder of such dimensions completely.

sent through the low-resistance galvanometer would cause a throw of 186 millimeters of the scale, and a throw of 1 millimeter corresponded to a flux of about 0.74 maxwells through the steel. The vertical unit in the diagram for the lines OGF, OAB, is 15 maxwells. It is evidence of the extraordinary magnetic softness of this specimen that whereas the flux through the rod corresponding to the point C was 70,000 maxwells, this sank to 113 maxwells when the current was slowly removed.

Figure 5 represents the results of experiments upon a soft steel shell about 12 centimeters long, 2.83 centimeters in outside diameter, and

1.9 centimeters in diameter inside. OCL represents the flux through the central cross section of the shell when the current was running, and the lower curve shows the residual flux upon a relatively larger scale. This residual flux is reversed for solenoid fields less than about 200 gausses.

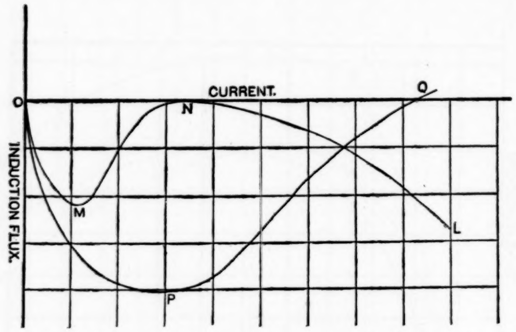

FIGURE 7. This diagram shows magnetic bias in a short rod of cold-drawn mild steel. This resisted the ordinary processes for demagnetizing the iron.

The three pieces of steel to which the curves of Figures 3, 4, and 5 belong were all freshly annealed just before they were magnetized, and the same precaution was taken in the case of almost every other specimen mentioned in this paper. The most careful reannealing does not generally bring a stout piece of iron which has been exposed to a strong field exactly back to its original magnetic state, though the differences are often so small as only to be discoverable when the specimen is tested for anomalous magnetization. Figure 6 shows such a test made upon a soft piece of Bessemer steel freshly annealed before the observations recorded in each curve. The residual moments were themselves very small and the differences were in absolute value very small indeed but are evidently real.

Figures 7 and 8 show the results of experiments made upon two pieces 12 and 8 centimeters long, respectively, cut from a rod of cold-rolled shafting about 3 centimeters in diameter. Each piece was exposed to a long series of magnetic fields alternating in direction and gradually decreasing in intensity, with the hope that this process would remove any magnetization that the rod might have acquired in the making, but both pieces show a decided bias which was too strong to yield to such treatment. In Figure 7, OPQ is the residual magnetism after currents which have caused positive moments have been

suddenly destroyed. OMNL shows the remanent magnetism after currents which have caused negative moments. The first curve indicates that the residual magnetism was reversed in sign, but this was never the case after negative currents. In Figure 8 similar curves are shown for the shorter specimen and it appears that some of the nega-

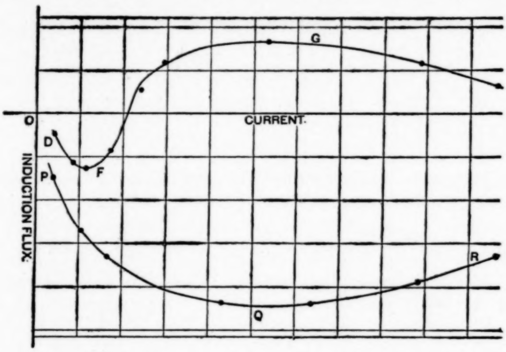

FIGURE 8. Magnetic bias in a rod of cold-rolled shafting which the demagnetizing process used could not remove.

tive currents left anomalous residuals. Annealing removed the bias from the first piece almost completely.

Apart from details the observations recorded in this section are in general agreement with much that has been written upon this subject as given [8] in Wiedemann's *Elektricität.* Wiedemann denotes by T the total magnetic moment of a bar when exposed to the action of a magnetizing field and by P the residual moment after the field has disappeared. He uses the suffixes a and f to denote that the moment of which he is speaking has been reached by a gradual change in the exciting field or by a very sudden one. He says that T_f is always larger than T_a and P_a than P_f, algebraically considered, but these differences are only large in short rods. P_f is slightly increased if the rod to be magnetized is surrounded by a thick tube of nonmagnetic metal. $(P_a - P_f)/P_a$ is smaller for bundles of insulated soft iron wire than for solid rods of the same dimensions. Inversion comes with longer rods when the exciting field is weak than when it is strong. Some of these statements will need to be discussed in the light of experiments upon divided cores. The statement copied by Wiedemann

[8] Bd. iv, §§ 338–340.

that if the iron core has been already magnetized in the normal direction by a current which has been slowly brought to zero, anomalous magnetization does not occur when a second current is applied in the same direction and then suddenly stopped, runs counter to all our experiences. Specimens which have not been really demagnetized show, of course, all sorts of abnormal behavior, but we have found it easy, with suitable cores, to get reversals after a slowly applied current has been slowly removed, by breaking suddenly a current in the same direction whether this last was applied slowly or suddenly. If a quickly applied current has been slowly cut off, we can get reversals by quickly breaking a current in the old direction, applied either quickly or slowly. If we apply either slowly or quickly a current in a fixed direction, then open it suddenly, and repeat this process a score of times, the reversal usually occurs at every break of the circuit without any reversal in direction of the exciting current. The remanent magnetism after a slow break, is greater if the current was quickly applied, but, as we have seen and as Wiedemann's statements would lead us to expect, anomalous magnetism occurs more regularly if the current has been slowly applied.

As Righi pointed out in 1880, if one cuts a number of pieces of different lengths from a stout steel rod and, beginning with the longest and taking them in order, tests the sign of the remanent magnetization of each after the exciting field has been suddenly destroyed, one often arrives at a length where anomalous reversals begin and continue for shorter pieces. Figures 9, 10, 11, are founded upon a set of such tests made upon rods cut from the very soft bar which furnished the specimen to which Figure 4 belongs. The diameter of the bar was about 2.83 centimeters, and the lengths, in centimeters, of the pieces used were 40.1, 31.8, 20.9, 18.0, 13.6, 12.0, 10.0, and 8.0. Figure 9 shows the residual fluxes through the centres of the pieces for all the specimens except the first and the fifth. These are all reversed in sign, but the amounts are extremely small because of the remarkable softness of the material. The horizontal unit corresponds to a solenoid field of 20 gausses, the vertical unit is about 7 maxwells. The first piece, 40 centimeters long, showed a slight reversed moment for excitations in the solenoid up to about 38 gausses, but the ordinates of the positive loop were not so high as the other curves of the series might lead one to expect them to be. Figure 10 shows the residual fluxes after the exciting currents had been slowly reduced to zero. The horizontal unit is here 80 gausses and the vertical unit 30 maxwells. Figure 11 shows the induction fluxes through the cross sections of the rods while they were in the magnetizing fields. The horizontal unit is in this case 80

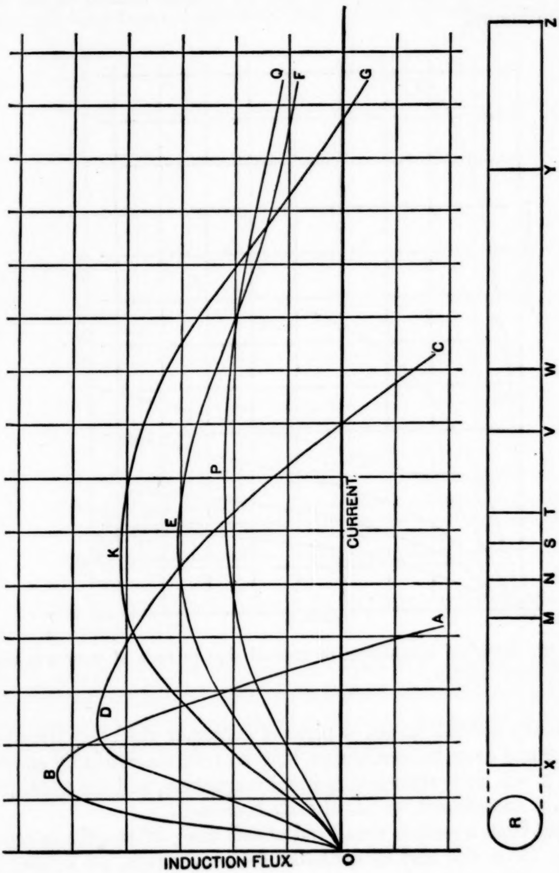

FIGURE 9. Abnormal residual magnetization in rods of very soft mild steel, about 3 centimeters in diameter and of different lengths.

gausses and the vertical unit very nearly 14,000 maxwells. Of 42,000 maxwells which the 8 centimeter long piece had under an exciting current of 16.4 amperes, only about 55 maxwells remained when the current had been gradually destroyed, and this for a cross section of about 7 square centimeters.

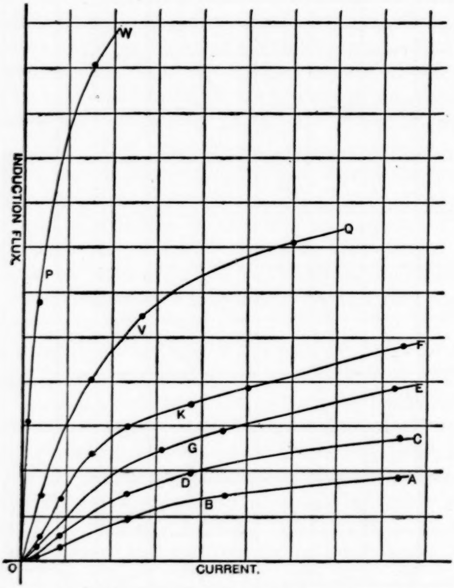

FIGURE 10. Residual magnetism of normal sign in rods of very soft mild steel of different lengths.

It is usually difficult to get a piece of Bessemer steel 3 centimeters in diameter and even 30 centimeters long so soft, magnetically considered, that it will show abnormal residual magnetism, and the metal just mentioned is exceptional, as has already been said.

Pieces cut from a certain round rod of soft steel, of lengths in centimeters 30, 15, 8, 6.8, and of diameter 1.6 centimeters, all refused to reverse when tested, but reversal finally appeared in a piece about 6.4 centimeters long.

It is often impossible to make a stout piece of hardened tool steel reverse unless its length be made so small that the observations become

doubtful. The next table (Table II.) records the results of observations made upon a certain piece of glass-hard tool steel, 12 centimeters long and 3 centimeters in diameter. The solenoid used in this experiment, one of a large number at our disposal, was 176.2 centimeters long and had 5526 turns of insulated wire divided up into three coils of 1837,

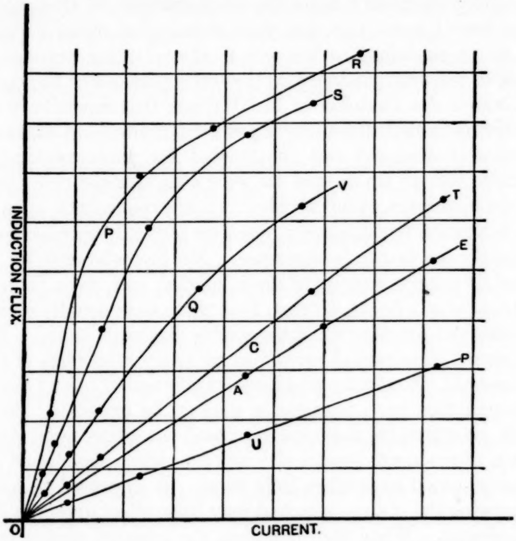

FIGURE 11. Magnetism induced by different exciting fields in a set of rods of various lengths.

1847, and 1847 turns respectively. The first column gives the intensity of the exciting current and the second column, on an arbitrary scale, the remanent magnetism, which always had the sign of the magnetizing field which had just been suddenly interrupted.

TABLE II.

I.			N.
0.2	2	2.0	98
0.4	6	2.5	148
0.6	17	3.0	196
0.8	23	4.0	302
1.0	31	5.0	415
1.5	61		

There is here no trace of anomalous magnetization.

If a strong current running through a solenoid containing a core of magnetizable metal, be suddenly broken, there will be, under favorable circumstances, an oscillatory discharge across the spark gap, and according to Wiedemann's theory, which was based upon the numerous experiments of early observers [9] upon the magnetization of steel needles by discharges from Leyden jars, the phenomena of anomalous magnetization are to be explained by the action of oscillating currents rapidly decreasing in intensity, induced in the outer portions of the core under test. Through the kindness of Mr. William Otis Sawtelle, who has a large revolving mirror driven by a powerful motor, and devices which he has himself designed and constructed for photographing electric sparks under various conditions, we were able to make sure that in the cases of the apparatus which we used in our experiments upon anomalous magnetization the discharge, when we suddenly opened the circuit, was uniformly oscillatory in character. Mr. Sawtelle and Mr. Coulson photographed a large number of these sparks; and, from their results, there cannot be any doubt, I think, that there were usually several hundred reversals in direction while the visible discharge lasted. With one of our solenoids, the period proved to be about 1/58000th of a second, and Professor G. W. Pierce, who most kindly tested one of our coils by itself, showed that such frequencies were to be expected. In each of the spark photographs, the record crossed the plate many times and the growth of the spark length with the time when the circuit was suddenly opened could be studied from them. It appeared that the manner of throwing the circuit open had very little effect upon the character of the discharge. When the current in the solenoid circuit is brought to zero by the continuous introduction of more resistance into the circuit, we do not expect that alternative currents will be induced in the core. It is difficult, however, to get any satisfactory theory upon which to base a mathematical investigation of the results of currents induced in a core of soft iron by oscillations decreasing in amplitude in a neighboring circuit. Even if the courses of such currents in a non-magnetizable core could be satisfactorily treated, and this seems difficult without a more accurate knowledge than we have about the behavior of the exciting current oscillations, we should not have any clear light

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[9] Savary, Ann. de Chim. et de Physique, **34**, 1826. Von Liphart, Pogg. Ann., **116**, 1862. Paalzow, Pogg. Ann., **117**, 1862. Reiss, Pogg. Ann., **122**, 1864. J. Henry, Scientific Writings, pp. 203 and 293. Rayleigh, Phil. Mag., **38**, **39**, 1870. Rutherford, Phil. Trans., **189**, 1897. Wilson, Electrician, **51**, 1903. Fleming, Proc. Roy. Soc., **74**, 1903.

upon what happens in a core magnetized in lines which are often closed within the metal, after the magnetizing current has been removed and the changes which come from the rapidly changing demagnetizing forces from the ends of the core itself are going on. We may content ourselves at present, therefore, by showing that, so far as we know, oscillations are always present in the circuit of the exciting current when anomalous magnetization is afterwards to be detected in the core. We must not close our eyes, however, to the fact that the demagnetizing forces due to the magnetic distribution itself complicate the problem.

Residual Magnetization in Bundles of Fine Iron Wire.

The remanent magnetism in a bundle of fine iron wire so shellacked as to prevent electric flow from one wire to the next, should be interesting because the effects of eddy currents in the core itself are nearly avoided. Fromme's work in this direction seems not to have been conclusive, and it will be instructive to consider two or three experiments.

Two similar solenoids were placed horizontal with their common axis perpendicular to the meridian, and with their nearer ends about 15 centimeters apart. These solenoids were so connected in series that a current sent through the circuit did not affect the needle of a magnetometer between them. A bundle of fine, varnished iron wire forming a cylinder 12 centimeters long and 3 centimeters in diameter was then introduced into one of the solenoids and tested to make sure that it had been properly demagnetized. A small current was next sent through the circuit and the wire put several times through the cycle corresponding to this current. Then the circuit was suddenly broken so as to bring the current from its full value to zero and the needle deflection caused by the residual magnetism was observed. This process was then repeated for a series of currents of increasing strengths. The results of the work are given in Table III. H represents the strength which the current would cause in the solenoid if the disturbing effects of the iron itself were not present. D shows the deflections of the needle on its scale caused by the residual moments. It is evident that there was nothing here similar to the abnormal magnetization of a soft iron solid cylinder of the same dimensions under similar conditions.

TABLE III.

H.	D.	H.	D.
10	19	150	182
19	45	211	208
37	81	301	233
63	112	420	253
89	138	530	263
110	156		

A bundle of the same size as the last (12 centimeters long and 3 centimeters in diameter) was then made of pieces 12 centimeters long cut from Bessemer steel wire some of it 2.4 millimeters in diameter and some of it twice as large. In this case the wires were not varnished and eddy currents were not wholly prevented. The observations were made by determining the induction flux through the central cross section of the bundle, first, when the exciting current was running and then after it had been suddenly destroyed. The first column in Table IV. gives the strength of the field in the solenoid ($4\pi nI/10$); the other columns give, on an arbitrary scale, the flux values.

TABLE IV.

H.	N.	N′.
10	293	6.8
19	592	15.0
36	1144	30.1
60	1900	52.0
84	2740	71.6
108	3490	87.2
145	4700	113
201	6900	140
290	9200	166
400	13800	188
501	17300	210

These results represent very fairly all our experiences with bundles of iron wire. Although most transformers show the von Waltenhofen phenomena unless the cores are very minutely divided, I have never been able to get even an approach to a reversal of sign of the magnetism of the short packages of fine wire that I have used. One of these, which was about 3 centimeters in diameter, was only 6.8 centimeters long.

In a stout iron cylinder made up of a small number of large pieces, anomalous magnetism is frequently to be found. Figure 12 shows the results of an interesting test upon a short cylinder of soft Bessemer steel, at first solid and then slit in a milling machine lengthwise with a very thin saw. The forms of the curves which show the magnitudes of the anomalous magnetization in these cases are similar, but the effect of the slits is very marked.

As has been already explained, we usually opened a circuit, when this had to be done suddenly, by a sharp blow upon a switch, but we experimented with other devices without finding that any of them was

better. At one time we broke the current by shattering a short piece of glass-hard steel wire introduced for the purpose into the circuit, but we did not discover that this process led to different conclusions from those which we reached with the more convenient key.

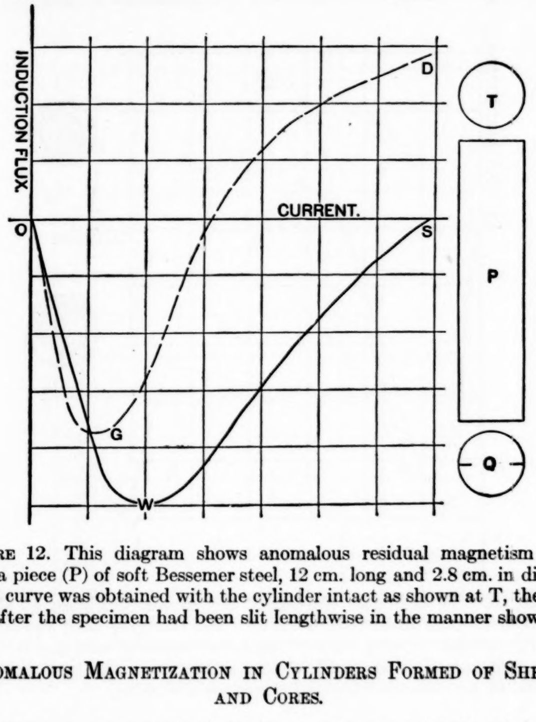

FIGURE 12. This diagram shows anomalous residual magnetism in the case of a piece (P) of soft Bessemer steel, 12 cm. long and 2.8 cm. in diameter. The full curve was obtained with the cylinder intact as shown at T, the dotted curve, after the specimen had been slit lengthwise in the manner shown at Q.

ANOMALOUS MAGNETIZATION IN CYLINDERS FORMED OF SHELLS AND CORES.

As will appear more clearly in the sequel, many of the lines of polarization in a short, anomalously magnetized solid cylinder form closed curves wholly inside the metal, and a cut made in the iron in the form of a cylindrical surface coaxial with the surface of the specimen would seriously interfere with this arrangement because there would be a very sensible reluctance at the crack. We should expect, therefore, that the magnetic characteristics of an iron cylinder formed of a cylindrical core and a coaxial shell would be in some respects different from that of a solid cylinder, and this is the fact.

Figure 13 gives two curves, the first, OKED, belonging to a shell of diameters 2.83 and 1.93, with a core of diameter 1.60 centimeters; the second, OGPQ, to a shell of diameters 3.20 and 2.20, with a core of diameter 1.90. In each of these cases the residual magnetism is reversed in sign for comparatively small currents, then direct for currents

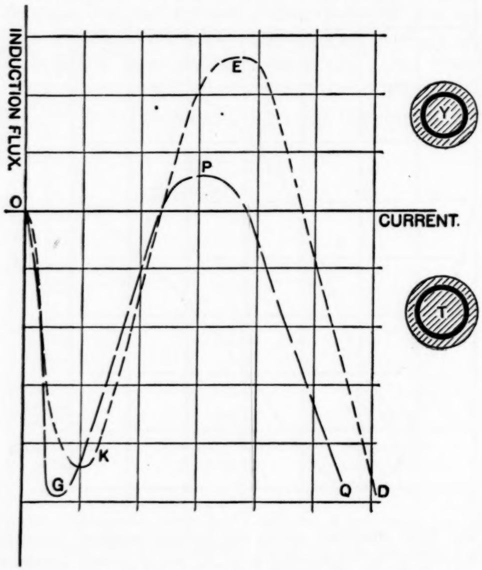

FIGURE 13. The ordinates of each of the curves of Figure 13 show the remanent magnetism in a combination of a soft Bessemer shell and core when the slowly applied exciting current has been suddenly broken. A negative ordinate indicates that the residual magnetism has a sign opposite to that of the field in the solenoid when the current was running.

somewhat stronger, and for large currents is again reversed with no apparent desire to become again positive. Curve LMNZ of Figure 14 belongs to a shell of diameters 2.83 and 1.93 with a core of diameter 1.90. The gap between core and shell is here narrower than in the cases just mentioned, and the curve which gives the magnitude of the residual magnetization in terms of the exciting current, while of the same general form as those of Figure 13, does not cross the axis of abscissas, and the residual moment is reversed for all the excitations shown in the curve.

Figure 15 shows some observations made upon a shell and core which were not very successfully demagnetized. A slight bias exists : ABC and PQZ show the residual fluxes through shell and core, the first for currents which give a negative moment while they are running, the second for positive currents.

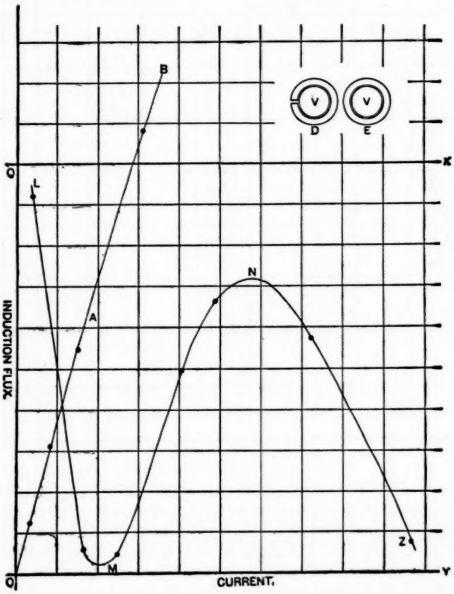

FIGURE 14. Two similar shells of soft steel, one intact, the other slit lengthwise by a thin saw cut, were used successively over the same core. LMNZ and OAB show the fluxes through the combinations in the two cases.

Figure 16 shows how greatly the manner of building up the current, which is then to be quickly broken, affects the amount of the negative or reversed magnetizations. Both of these curves show anomalous magnetization for moderate currents, but the residual flux is very much greater if the current is built up gradually than if it is built up suddenly.

The gap between core and shell in the combinations X and Y of Figure 13 and some others we have used, was purposely made wide enough to permit of the introduction of a very thin ring coil to em-

brace the core alone and thus make it possible to study separately the behavior of each part of the system. The results of experiments of this kind proved instructive, as will appear from an account of a typical case.

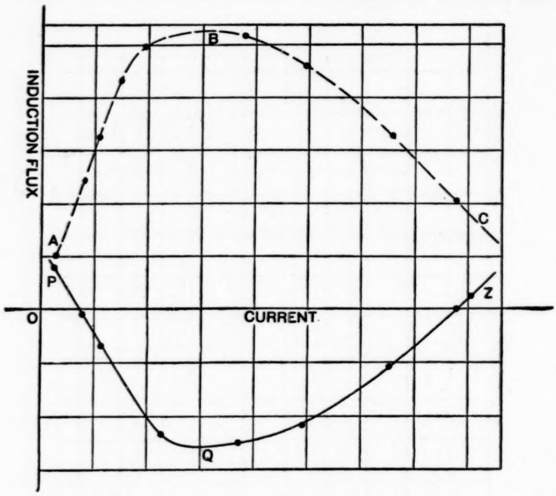

FIGURE 15. A combination of shell and core, made of soft Bessemer steel, was demagnetized as completely as possible and then tested in a long solenoid. The magnetizing current was built up gradually and then suddenly broken. The ordinates of ABC show the residual flux through the metal when the current gave a negative moment before it was interrupted, the ordinates of PQZ show the remanent flux for oppositely directed currents. There was a bias in the specimen which showed that the process of demagnetizing it had not been wholly successful, and the anomalous magnetization is of different magnitude on the opposite sides.

A cylindrical shell 12 centimeters long, the diameters of which were 3.00 and 2.27 centimeters, was used with a core 1.90 centimeters in diameter to form a combination (Z) which, after being thoroughly demagnetized, was placed in a long solenoid and exposed to a series of magnetizing fields, each a little stronger than the preceding. At every step, the metal was put a number of times through the hysteresis cycle corresponding to the exciting current employed, and then the fluxes through the central cross sections of core and shell were measured while the current was running. In Table V. H represents the

field ($4\pi nI/10$) due to the current in the solenoid, F is the flux in maxwells through the combination of core and shell, N is the flux through the core alone, and N′ is the flux which the core would carry if the whole flux through the system were uniformly distributed. The area of the cross section of the core was about 47 per cent of that of the combination.

TABLE V.

H.	F.	N.	N′.	N/F.
10	1270	130	595	0.102
20	2500	215	1170	0.086
30	3670	295	1720	0.080
40	4830	365	2270	0.076
50	5990	430	2820	0.072
60	7150	500	3360	0.070
70	8310	565	3920	0.068
80	9470	630	4450	0.067
90	10640	700	5000	0.066
100	11820	765	5500	0.065
125	14800	930	6950	0.063

While the slowly built up current is running steadily the flux in the core, which should be nearly half that through the whole combination if the flux is to be uniformly distributed, is very much less.

When in the case of this combination (Z), the slowly built up current, so directed as to make the flux positive while it is running, is very slowly decreased to zero, the remanent flux through the system is positive, but the flux in the core becomes *negative*, in the manner indicated by the figures in Table VI. in which F, N, S, are the induction fluxes through the whole combination, the core, and the shell, respectively.

TABLE VI.

H.	F.	N.	S.
50	+ 86	−322	+408
100	+122	−410	+530
150	+132	−370	+500
200	+141	−318	+459
250	+149	−265	+415
300	+155	−213	+368

While the remanent flux through the system increases regularly with the strength of the current, the oppositely directed fluxes in the shell and the core decrease after reaching maximum values.

In all work with short bars of iron or steel, the "demagnetizing force due to the ends" becomes very important. The outer portions of a very short magnet often reverse the direction of the polarization in the inner portion so that most of the lines of polarization are closed within the metal and the effect of the magnet upon a magnetometer

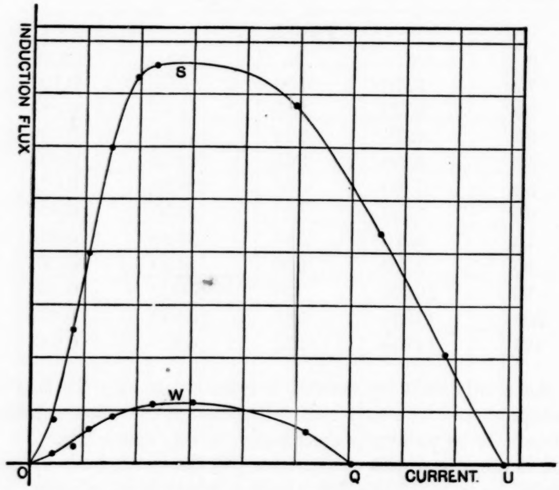

FIGURE 16. A shell and core of soft Bessemer steel about 12 cm. long were exposed to a magnetizing field of given strength in a long solenoid, and the exciting current was then suddenly broken. The ordinates of the curves OSU and OWQ represent the remanent induction flux through the central cross section of the specimen, when the solenoid current was slowly built up and suddenly applied, respectively. A positive ordinate represents a reversal of magnetism in these curves.

needle is often very slight indeed. If a cylindrical shell with a core of loose steel wires be placed inside a solenoid of stout wire and a powerful current be then suddenly sent through the coil, the wires will be thrown violently out of the shell if the latter be short and stout, in a direction which shows that the moment induced in them by the exciting current was opposite in sign to that of the shell. This experiment is sometimes very striking.

If, in the experiments upon the combination Z, the exciting current was suddenly destroyed, the flux in the shell became instantly *negative*,

while the remanent flux in the core was *positive* just as it was when the current was running through the solenoid circuit. See Table VII.

TABLE VII.

H.	F.	N.	S.
10	− 7	+ 57	− 64
20	−18	+134	−152
40	−25	+180	−205
50	−21	+184	−205
100	− 5	+178	−183
150	+ 4	+170	−166
200	− 4	+171	−175
250	−17	+214	−231
300	−30	+320	−350

At $H = 1100$ gausses F gave a negative throw far off-scale, and N a similar positive throw. At this excitation, however, the solenoid current had to be so strong as to heat the coil rapidly and we did not attempt to make careful determinations of these fluxes. If F were plotted against H we should get a curve of the form shown in Figure 13.

All the combinations of shell and core that we have used give a set of fluxes for the F column which vary with the excitation in much the same way that the whole flux for Z does. There is always — so far as my knowledge goes — an increase in N from a low value near the outset to a rapidly increasing one at high excitations, but sometimes the increase is regular and sometimes not. As an instance of a very rapid increase in N beginning near a given excitation, I may cite the case of

TABLE VIII.

I.	F.	N.
0.22	− 1 8	+ 14
0.42	− 4.7	+ 33
0.82	−12.2	+ 78
1.44	−16.3	+118
1.77	−18.0	+138
2.25	−17.2	+148
2.73	−15.7	+162
3.43	−10.1	+177
5.00	+ 2.7	+197
7.60	+10.3	+308
12.10	−20.1	+664

a certain combination of nearly the same dimensions as Y of Figure 13, which was tested in a solenoid for which $4\pi n/10$ was very nearly equal to 25. The first column in Table VIII. gives the intensities of the exciting currents used, the second and third columns the fluxes after the currents had been suddenly interrupted.

L in Figure 17 represents a combination of two coaxial shells and a core, very accurately made and carefully annealed by Mr. Thompson. The diameters, in centimeters, of the five cylindrical surfaces were 1.12, 1.58, 2.53, 3.00, 3.96. This system was treated like all the other test pieces and the fluxes through all three members were determined after the currents which had been slowly applied had been slowly brought to zero and again after they had been suddenly destroyed. Tables IX. and X. give the remanent fluxes for the slow breaks and for the quick breaks respectively. I represents the solenoid current in amperes.

TABLE IX.

I.	Core.	Inner Shell.	Outer Shell.
0.60	− 7.8	− 38	+ 58
1.41	− 25.6	−160	+225
4.70	− 56.5	−292	+428
8.50	− 84.0	−276	+474
17.00	−156.0	− 34	+294
44.50	− 41.4	+215	+ 47

TABLE X.

I.	Core.	Inner Shell.	Outer Shell.
0.60	+ 6.2	+ 83	− 109
1.41	+ 12.1	+ 174	− 223
4.70	− 2.5	+ 299	− 318
8.50	− 0.7	+ 364	− 366
17.00	+ 1.9	+ 652	− 674
44.50	+155.0	+1445	−1922

The signs are nearly all different according as the current is slowly or quickly destroyed.

The observations already described represent fairly all our work upon combinations of solid shells and cores and it remains to mention the special case represented by the nearly straight line of Figure 14. Here the shell was of the same dimensions and of similar material as that used in the work which led to the curve LMNZ in the same figure, but this shell was slit through lengthwise by a single saw cut which prevented currents from circulating around it. Many of our

specimens were made 12 centimeters long so that our observations might be more easily comparable with some which von Waltenhofen and Fromme made.

We have seen that if in a combination of a shell and a core the exciting current be gradually reduced to zero, the residual magnetiza-

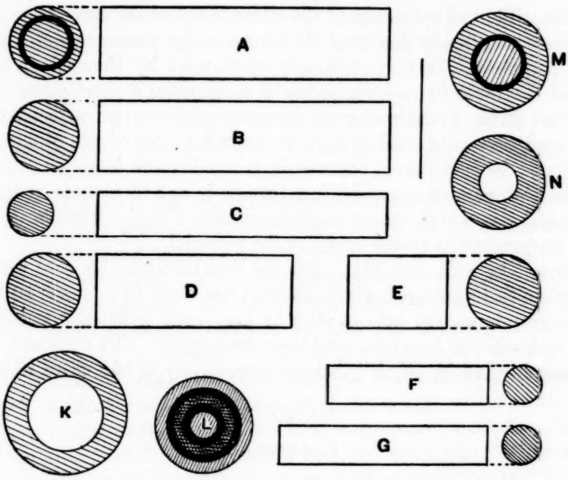

FIGURE 17. The forms of some of the test pieces.

tion of the shell is usually normal and that of the core reversed. If, however, the current is suddenly broken, the magnetization of the shell is often reversed and that of the core is normal. These facts may be proved by removing the specimen from the solenoid and testing the two pieces which then seem to be strongly magnetized, separately with a compass or magnetometer. The separation of the members of the system alters the polarization in each, however, and the process is not to be recommended in accurate work.

It is very difficult to study the residual magnetism in a very short, stout soft iron cylinder, whether this be normal or anomalous, by the use of iron filings, for since so many lines of polarization are closed within the metal, the external action of the magnetization is usually small. In the case of a combination of a shell and a core, where the gap prevents the arrangements of polarization from being what they would be in a solid cylinder of the same dimensions, it is often practi-

cable to show by the aid of very fine filings that lines emerge into the air from the outer filaments at one end of the specimen and go into the metal again at the same end at points nearer the axis.

The Influence of an Iron Shell upon the Magnetic Behavior of a Short Cylinder within It.

Some mild steel cylinders of the dimensions of the cores used in the combinations already described do not show the phenomenon of anomalous magnetization very strikingly when used by themselves, and it seemed desirable to make a series of tests upon a short piece of very soft steel about 3 centimeters in diameter, without and with shells. I have used very mild steel of various kinds for most of the observations mentioned in this paper, because it is much more homogeneous than the best procurable wrought iron, which is apt to include patches of oxide and slag which hinder the free passage of eddy currents in directions perpendicular to the grain of the material.

Tables XI., XII., and XIII., give the flux through this core when the slowly applied current I, which created the field $H = 4\pi n I/10$ within the solenoid, was in action, after it had been gradually reduced to zero, and after it had been suddenly destroyed. The numbers in the columns headed N, N′, N″, belong respectively to the cases where the

TABLE XI.

Current On.

H.	N′.	N″.	N‴.
40	+ 3110	+ 747	+ 681
65	+ 5450	+1120	+1012
176	+14480	+2560	+2330
370	+31200	+5360	+4740
452	. . .	+6720	+5850

TABLE XII.

Slow Break.

H.	N.	N′.	N″.
20	+ 8	− 12	− 25
50	+ 20	− 42	− 97
100	+ 35	−142	−173
150	+ 51	−191	−204
200	+ 66	−216	−223
300	+ 92	−233	−235
400	+105	−248	−242

core had no shell, where the shell of soft mild steel had the diameters 4.45 and 3.30; and where the shell made of fine, soft, varnished iron wires had diameters of 4.90 and 3.35 centimeters respectively.

TABLE XIII.

QUICK BREAK.

H.	N.	N′.	N″.
40	−18	+ 73	+ 74
65	−23	+106	+138
176	−18	+115	+209
378	+11	+ 30	+220
576	+42	+ 14	+216

In the solid shell the alternating eddy currents which Wiedemann had in mind may encircle the core, but this would not be possible in the core made of shellacked wire. It is evident that both shells exert a strong demagnetizing effect upon the core, even while the current is running in the solenoid. All the results here tabulated agree in general with those quoted in the last section. In the case of the solid shell, the moment of core and shell taken together will usually be reversed after certain strengths of current, but this is never the case when the shell is finely divided. Figure 18 shows a typical instance. The solid core is surrounded by a wire shell, and when the exciting current is suddenly destroyed the core has a reversed magnetization for values of H up to about 350 gausses, as is shown in curve OQR. The whole flux through the combination of core and shell as indicated by the curve OWV is never negative, though for high excitations, when the flux through the core is strongly positive, the flux through the shell itself may be small. In one case under an exceedingly high excitation, the line corresponding to OQR bent down again something like the curves of Figure 13, but the observations were so difficult to manage that I did not attempt to follow this out in other cases. A value of H above 1700 or 1800 is hard to maintain without heating the metal and the solenoid employed unduly, which masks the effect to be studied.

THE INFLUENCE OF A THICK COPPER SHELL UPON THE MAGNETIC BEHAVIOR OF A SHORT CYLINDER WITHIN IT.

Many years ago Fromme enclosed a stout piece of soft iron which he was testing in a thin shell or shield of copper and was able to prove that this shell did not prevent the iron from showing anomalous magnetization when the magnetizing field about it was suddenly destroyed.

Our experiences agree with his if the shell is very thin, but seem to show that a thick enough copper shell will always prevent a reversal of the magnetization in a soft iron core inside. The records of experiments on two or three specimens of soft steel with shells of different thicknesses will make clear the nature of the phenomena.

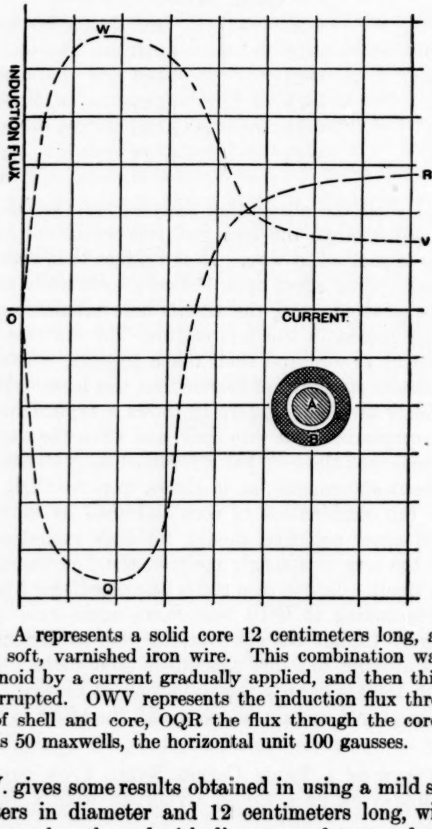

FIGURE 18. A represents a solid core 12 centimeters long, and B, a shell made of fine, soft, varnished iron wire. This combination was magnetized in a long solenoid by a current gradually applied, and then this current was suddenly interrupted. OWV represents the induction flux through the central section of shell and core, OQR the flux through the core alone. The vertical unit is 50 maxwells, the horizontal unit 100 gausses.

Table XIV. gives some results obtained in using a mild steel cylinder 1.9 centimeters in diameter and 12 centimeters long, with a copper shell of the same length, and with diameters of 3.80 and 2.90 centimeters. The second and third columns give the fluxes in maxwells through the central cross section of the iron when the exciting current has been slowly, and quickly, brought to zero.

TABLE XIV.

CORE INSIDE SHELL.

H.	Slow Break.	Quick Break.
22	+14.9	+ 5.5
39	+29.6	+13.3
60	+57.2	+24.3
170	+73.3	+45.0
255	+79.0	+52.7
430	+91.7	+72.5

When the shell was removed the fluxes were those given in Table XV.

TABLE XV.

CORE ALONE.

H.	Slow Break.	Quick Break.
22	+13.5	− 9.6
39	+25.3	−17.7
100	+54.0	−14.2
218	+64.0	+13.6
430	+73.8	+48.3

The eddy currents in the copper made the gradual reduction of the current by the introduction of resistance into the circuit more continuous and prevented the magnetizing field from vanishing suddenly when the circuit was broken.

A freshly annealed piece of Bessemer steel 1.6 centimeters in diameter and 12 centimeters long was tested alone, and inside each of two copper shells of its own length, with wall thicknesses of 1.20 centimeters and 0.47 centimeters respectively. Table XVI. shows the fluxes through the central cross section of the iron for slow removals of the excitation. The fluxes for the thick shell, the thinner shell, and for the core without any shell, are given in the columns headed A, B, C. Table XVII. gives the corresponding figures for the case where the exciting current was suddenly destroyed.

TABLE XVI.

SLOW BREAK.

H.	A.	B.	C.
38	+ 45.5	+ 42.4	+ 37.6
64	+ 84.2	+ 71.5	+ 67.0
168	+162.4	+126.0	+108.0
360	+207.0	+163.0	+112.5

TABLE XVII.

Quick Break.

H.	A.	B.	C.
22	+ 17.3	+ 7.0	−15.5
39	+ 33.4	+13.8	−27.4
64	+ 60.8	+20.6	−34.3
168	+127.0	+37.0	−18.9
360	+168.0	+81.5	+35.5

Only a few typical numbers are here given but these and many others are used in plotting the curves given in Figure 19. The line

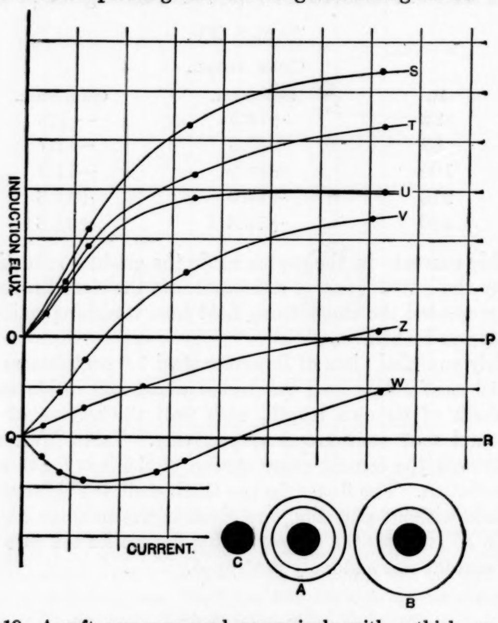

Figure 19. A soft core was used successively with a thick copper shell, with a thinner shell, and without any shell. OS, OT, OU show the remanent fluxes when the magnetizing fields were slowly removed; QV, QZ, QW the fluxes if the field had been suddenly destroyed.

QW which has QR as its horizontal axis shows the reversed magnetization when the core has no shell. OS, OT, OU show the fluxes for slow breaks, QV, QZ, QW for the quick breaks.

As has been already explained, some of our slow breaks were made continuously with the help of a specially constructed rheostat, and others, sufficiently well for the purposes, by introducing, by relatively small steps, a series of resistances into the circuit. This last process which was not, of course, perfectly continuous, was used in the experiment recorded in Tables XVI. and XVII. and the effect of the copper in preventing any sudden change in the induction flux in the iron is evident from the figures given.

Although many complications may occur if a piece of iron or steel to be tested has a magnetic bias, or has not been uniformly tempered, the experiments described in this paper seem to lend support to the theory that the residual moment of an originally neutral bar which has been magnetized in a solenoid, is always norm al unless the current onits way to extinction oscillates to and fro. When the exciting current is destroyed without oscillating in direction, even though the process be finished in a small fraction of a second, the remanent magnetization has the same sign as the magnetizing field. It appears that a bundle of very fine soft iron wire cannot be made to show anomalous magnetism and that a thick copper shell placed over a solid bar of magnetizable metal prevents reversals of magnetism under circumstances which would produce them if the shell were away.

It seems probable that in a short, stout rod of iron or steel exposed to a magnetizing field, the intensity of magnetization in the inner portions is less than in the outer filaments and that usually when the field is removed the direction of the polarization at the axis is opposite to that of the polarization at the outer surface. The direction of the lines at the outer surface may be normal or anomalous according to the manner in which the exciting current comes to its end, but in any case many of the lines of magnetization form closed curves wholly within the metal.

The placing of a thick iron shell either solid or constructed of fine insulated wire, about a core exposed to a magnetizing field, reduces the flux through the core, and, if the exciting current be reduced gradually to zero, the shell usually reverses the sign of the moment which the core would otherwise have had. If the circuit of the exciting current be suddenly broken, the residual magnetism of the core is often changed in sign by the presence of the shell. A finely divided iron shell never acquires anomalous magnetization when its exciting current is suddenly destroyed, but such a shell acts magnetically upon either a

solid or a divided core and often reverses the sign which the core would have without it.

It is difficult to make even short, stout pieces of glass-hard tool steel show anomalous magnetization, and it is impossible to reverse the magnetism of very long pieces of soft iron where the end effects are not sensible.

The experiments of Mr. L. A. Babbitt, as well as previous experiments of our own, seem to show conclusively that none of the von Waltenhofen effects are to be looked for in massive transformer cores if these are made of fine varnished wire. I have never seen anomalous magnetism in a uniformly annealed closed ring.

It is evident that if the solenoid current in a test for anomalous residual magnetism be suddenly broken, the change in the electromagnetic field in the iron is much more rapid when the core is made of lengths of fine, varnished wire than when it is solid and eddy currents in it shield the inner filaments. Indeed, if the core be made of wires of a uniform size, the average rate of change of H with the time is roughly proportional to the area of one wire. If, however, the circuit be suddenly closed, the change in the field in the iron caused by the exciting current cannot be made instantaneous even if eddy currents be wholly shut out, and the effect of dividing the core is not so striking. If the magnetized particles of a piece of iron are imbedded in a quasi viscous medium, the rapidity of the changes in the forces acting upon the molecules should affect the magnetic properties of the iron.

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